

EIGENVALUES OF WORDS IN TWO POSITIVE DEFINITE LETTERS

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ABSTRACT. The question of whether all words in two real positive definite letters have only positive eigenvalues is addressed and settled (negatively). This question was raised some time ago in connection with a long-standing problem in theoretical physics. A large class of words that do guarantee positive eigenvalues is identified, and considerable evidence is given for the conjecture that no other words do. In the process, a fundamental question about solvability of symmetric word equations is encountered.

1. INTRODUCTION

A *word* is a juxtaposed sequence of letters chosen (with repetition allowed) from a given alphabet. We shall be concerned here with an alphabet of two letters, $\{A, B\}$, so that a sample word would be $AABABBBAAAB$; thus, hereafter “word” means one over a two-letter alphabet. The *length* of a word is the total number of letters present (including repetitions); the sample word has length 10. We shall be interested in the combinatorial structure of words as abstract objects, but, often, we will interpret a word as the matrix resulting from the substitution of two independent positive definite matrices for A and B . The eigenvalues and trace of the resulting matrix will be our primary interest.

The initial motivation comes from a chain of three questions raised by Lieb [L], stemming from issues in quantum physics [BMV]. In addition Pierce raised Question 3 below from an independent source [P]. The three questions are the following:

Question 1. Does the polynomial $p(t)$, defined by $p(t) = \text{Tr}[(A + Bt)^m]$, have all positive coefficients whenever A and B are positive definite matrices?

Since the coefficient of t^k in $p(t)$ is the trace of the sum of all words in A and B with length m and k B ’s, the following, which could help answer Question 1, has also been asked [L].

Question 2. Is the trace of a given word positive for all positive definite A and B ?

Since a matrix with positive eigenvalues necessarily has positive trace, a yet more precise question has also been raised [L], [P].

Question 3. Are all the eigenvalues of a given word positive for all positive definite A and B ?

In addition, these particular questions and a number of natural issues they raise seem central to matrix analysis. Since we became interested in them (thanks to Lieb and Pierce), we have learned that a number of different investigators (including

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us) have tested them empirically by trying many different words and calculating the eigenvalues for many (tens of thousands) different randomly generated pairs of matrices of different sizes. To our knowledge, no one turned up a counterexample via such simulation, rendering Question 3 all the more interesting. Indeed, this apparent rarity of counterexamples surely means that something interesting is going on, and we have found that this area suggests many intriguing questions, a few, but not all, of which we discuss here.

We call a word *symmetric* if it reads the same right to left as left to right; e.g., $ABBABBA$ is symmetric, but $ABABBA$ is not (in other contexts, the name “palindromic” is also used). To simplify exposition, we shall often use exponents in the representation of a word; e.g., the symmetric word above might have been written AB^2AB^2A . We are principally concerned here with real symmetric positive definite matrices, though in many cases the complex Hermitian case is the same. We shall try to explicitly draw a distinction only when it is important. We intend to exploit differences in the complex Hermitian case in further work. Certain symmetries of a word do not change the eigenvalues, and, since eigenvalues are our interest, we shall freely use such symmetries and, often, only view two words as distinct if they are not equivalent via the following transformations:

- *Reversal*. Writing the letters of the words in reverse order. This corresponds to transposition of the matrix product and thus does not change eigenvalues.
- *Cyclic permutation*. Movement of the first letter of the word to the end of the word. This can be realized as a similarity of the word via the first letter and, thus, also does not change eigenvalues.
- *Interchange of A and B* . This may change the eigenvalues of a particular word, but, as A and B are both positive definite, it does not change the possible eigenvalues.

Note that a symmetric word is one that is identical to its own reversal. There are, for example, 20 words of length 6 with 3 A ’s, but only 3 that are distinct up to the above symmetries: $ABABAB$, A^3B^3 , and ABA^2B^2 .

Tangentially, we note that there is an algorithm for generating the equivalence class, relative to the above symmetries, of a word of length L or determining the number of distinct equivalence classes among N such words. Given a word W , another word V lies in its equivalence class if and only if V is the result of k cyclic permutations ($0 \leq k \leq L$), composed with (possibly) a reversal, composed with (possibly) an interchange, applied to W . This gives an algorithm of order $O(NL)$.

Since a symmetric word may inductively be seen to be congruent [HJ, p. 223] to either the center letter (if the length is odd) or to I (if the length is even), we have by Sylvester’s law of inertia the following.

Lemma 1.1. *A symmetric word in two positive definite letters is positive definite and, thus, has positive eigenvalues.*

It follows that any symmetric word gives an affirmative answer to Question 3.

It has long been known [HJ] that a product of two positive definite matrices (e.g., the word AB) has positive eigenvalues and is diagonalizable. We call a diagonalizable matrix with positive eigenvalues *quasi-positive* and record here a slightly more complete observation.

Lemma 1.2. *The n -by- n matrix Q is quasi-positive if and only if $Q = AB$, in which A and B are positive definite. Moreover if $Q = SDS^{-1}$, with D a positive*

diagonal matrix, then all factorizations AB of Q into positive definite matrices A and B are given by

$$A = SES^* \quad \text{and} \quad B = S^{-1*}E^{-1}DS^{-1},$$

in which E is a positive definite matrix that commutes with D .

Proof. If $Q = AB$, with A and B positive definite matrices, then Q is similar to $A^{-1/2}ABA^{1/2} = A^{1/2}BA^{1/2}$, which is congruent to B and, therefore, positive definite. Thus, Q has positive eigenvalues and is diagonalizable, as is so for a positive definite matrix.

If Q is quasi-positive, $Q = SDS^{-1}$, with D positive diagonal, then $Q = AB$, with $A = SES^*$ and $B = S^{-1*}E^{-1}DS^{-1}$ (E is a positive definite matrix commuting with D), both positive definite. Suppose that $Q = AB$ is some other factorization into positive definite matrices. So $B = A^{-1}Q$ is Hermitian. Then, $A^{-1}Q = Q^*A^{-1}$ or $AQ^* = QA$ or $AS^{-1*}DS^* = SDS^{-1}A$, so that $S^{-1}AS^{-1*}D = DS^{-1}AS^{-1*}$. Thus, $S^{-1}AS^{-1*}$ commutes with D ; call $E = S^{-1}AS^{-1*}$, and then $A = SES^*$. It follows that E is Hermitian and positive definite, as A is. Now, $B = A^{-1}Q = S^{-1*}E^{-1}DS^{-1}$, which is positive definite since $E^{-1}D$ is (because they commute). \square

We now know that the nonsymmetric word AB also positively answers Question 3, but much more follows from Lemmas 1.1 and 1.2. We call a word *nearly symmetric* if it is either symmetric or the product (juxtaposition) of two symmetric words. It is an interesting exercise that the nearly symmetric words are unchanged by the three symmetries (i), (ii), and (iii). There is also a simple algorithm to check for near symmetry: left to right, parse a given word after each initial symmetric portion and check the remainder for symmetry (counting the empty word as symmetric). We then have the following.

Theorem 1.3. *Every nearly symmetric word in two positive definite letters has only positive eigenvalues.*

Proof. The proof follows from Lemmas 1.1 and 1.2. \square

Are all words nearly symmetric? No, but all sufficiently short words are.

Theorem 1.4. *A word in which one of the letters appears at most twice is nearly symmetric.*

Proof. Without loss of generality, we examine the situation in which B appears at most twice. If a word contains only the letter A , the result is trivial. If the letter B appears only once, then the word will be of the form A^pBA^q ($p, q \geq 0$). If $p \geq q$, then we have $A^pBA^q = A^{p-q}(A^qBA^q)$, and if $p \leq q$, we have $A^pBA^q = (A^pBA^p)A^{q-p}$. In both cases, the word is nearly symmetric. In the case of two B 's, the word can be written as $A^pBA^qBA^t$ ($p, q, t \geq 0$), and so our word is one of the nearly symmetric words, $(A^pBA^qBA^p)A^{t-p}$ or $A^{p-t}(A^tBA^qBA^t)$. \square

In order to not be nearly symmetric then, a word must have length at least 6 and 3 each of A and B . Among the 3 such equivalence classes of words of length 6, one is actually not nearly symmetric, ABA^2B^2 , and this shows that Theorem 1.4 is best possible. This is the first interesting word relative to Question 3, and we have the following corollary.

Corollary 1.5. *Every nearly symmetric word, and thus every word of length < 6 has only positive eigenvalues.*

An interesting question one can ask is how many nearly symmetric words there are of a given length L . More importantly, what does the fraction of nearly symmetric words to the total number of words approach as L goes to infinity? The result can be found in [K], and it states that the number of nearly symmetric words of length L is $O(L \cdot 2^{(3/4)L})$. This gives us that the density of such words approaches 0, and therefore, as L goes to infinity, there is a pool of potential negative answers to Questions 2 and 3 that ever increases in relative frequency.

The situation is much simpler for 2-by-2 matrices, and we note (as does Pierce [P] and Spitkovsky [S]) the following.

Fact 1.6. *Both eigenvalues of any word in two 2-by-2 positive definite matrices are positive.*

Proof. We will actually show something stronger. Let W be any finite product of real positive powers of A and B , in which A and B are 2-by-2 positive definite (complex) Hermitian matrices. (Here, we take principal powers, so that W is uniquely defined.) We first preprocess the word as follows. Make one letter diagonal via uniform unitary similarity, and then make the other letter entrywise nonnegative via a diagonal unitary similarity. This does not change the first letter. Now, the word is nonnegative (as it is clear from the spectral theorem that a positive power of a nonnegative 2-by-2 positive definite matrix is nonnegative). If it is diagonal, there is nothing more to do (the diagonal entries are positive). If not, apply the Perron–Frobenius theorem (which says a positive matrix must have a positive eigenvalue [HJ, p. 503]) and the fact that the determinant is positive to show that the other eigenvalue is positive as well. \square

Corollary 1.7. *The polynomial $p(t)$, defined by $p(t) = \text{Tr}[(A + Bt)^m]$, has all positive coefficients whenever A and B are 2-by-2 positive definite matrices.*

This all suggests that careful consideration of the word ABA^2B^2 , or, equivalently, $(BA)(BA)(AB)$, for 3-by-3 positive definite A and B is warranted. This is equivalent, by Lemma 1.2, to the study of the expression C^2C^T for quasi-positive C . Since any real matrix with real eigenvalues may be upper triangularized by orthogonal similarity, it suffices to consider

$$C = \begin{bmatrix} a & x & z \\ 0 & b & y \\ 0 & 0 & c \end{bmatrix}$$

with $a, b, c > 0$. If a, b , and c are distinct, C is diagonalizable and thus quasi-positive. Using MAPLE, and with the assistance of Shaun Fallat, it was found that x, y, z and such a, b, c may be found so that $\text{Tr}(C^2C^T) < 0$. Consistent with prior empirical experience, choice of such x, y, z and a, b, c is delicate and falls in a very narrow range. Resulting A and B (see Lemma 1.2) that exhibit a negative answer to Question 2 (and, thus, 3) are, for example,

$$A_1 = \begin{bmatrix} 1 & 20 & 210 \\ 20 & 402 & 4240 \\ 210 & 4240 & 44903 \end{bmatrix} \quad \text{and} \quad B_1 = \begin{bmatrix} 36501 & -3820 & 190 \\ -3820 & 401 & -20 \\ 190 & -20 & 1 \end{bmatrix}.$$

The extreme and reverse diagonal progressions are typical of such examples. If the diagonal of one is “flattened” by orthogonal similarity, the progression on the diagonal of the other becomes more extreme.

We remark at this point that words giving a negative answer to Question 2 in the 3-by-3 case imply negative answers in the n -by- n case for $n > 3$. This allows us to restrict our attention to the 3-by-3 positive definite matrices. Simply direct sum a 3-by-3 example (giving a negative trace) with a sufficiently small positive multiple of the identity to get a larger example.

The idea of our first construction and some fortunate characteristics of the constructed pair allow the identification of several infinite classes of words giving negative answers to Questions 2 and 3. We indicate some of these next.

1. Any positive integer power of a word that does not guarantee positive eigenvalues also does not guarantee positive eigenvalues. For instance, this shows that $BABAABBABAAB$ can have a nonpositive eigenvalue. This is Theorem 1.8 below.

2. Suppose a word can be written in terms of another word T as $T^k(T^*)^j$ for $k \neq j$. Furthermore, suppose $T = S_1S_2$ is a product of two symmetric words S_1 and S_2 . Then if the simultaneous word equations

$$\begin{aligned} S_1(A, B) &= C, \\ S_2(A, B) &= D \end{aligned}$$

may be solved for positive definite A and B given positive definite C and D , then the original word can have negative trace. The first nontrivial application of this technique is the first counterexample, $(BA)^2AB$, in which $S_1 = B$, $S_2 = A$, $k = 2$, and $j = 1$. This result is Theorem 1.9 below.

3. Infinite classes involving single-letter length extension: this is a nice application of sign analysis. Our first result is the following.

(a) *The word, ABA^2B^{2+k} with k a nonnegative integer can have negative trace.*

Proof. A direct computation with A_1 and B_1 from above gives us that

$$(BABAAB)B = \begin{bmatrix} -164679899 & 17226460 & -856450 \\ 62354360 & -6523192 & 324340 \\ -5877450 & 614880 & -30573 \end{bmatrix}$$

has sign pattern

$$\begin{bmatrix} - & + & - \\ + & - & + \\ - & + & - \end{bmatrix}.$$

Next, notice that B_1 has the sign pattern

$$\begin{bmatrix} + & - & + \\ - & + & - \\ + & - & + \end{bmatrix}$$

and that

$$\begin{bmatrix} - & + & - \\ + & - & + \\ - & + & - \end{bmatrix} \begin{bmatrix} + & - & + \\ - & + & - \\ + & - & + \end{bmatrix}$$

is

$$\begin{bmatrix} - & + & - \\ + & - & + \\ - & + & - \end{bmatrix}$$

unambiguously.

Hence, multiplying the product $BABAABB$ by B on the right any number of times will preserve the negativity of the trace. Therefore, $BABAABB \cdot B^k$ gives a negative answer to Question 2 for all integers $k \geq 0$. \square

Proofs using the same technique give us many infinite classes of counterexamples, some of which we list below:

- (b) $ABABAAB^k$, $k \geq 2$.
- (c) $ABBABAAB^k$, $k \geq 2$.
- (d) $ABAABBAAB^k$, $k \geq 2$.

4. Recall the two matrices A_1 and B_1 giving $(BA)(BA)(AB)$ a negative trace. These matrices can also be used to prove that the words ABA^pB^q , $ABBABA^pB^q$, and $ABABA^pB^q$ can have a negative trace for all integers $p, q \geq 2$. Notice that (a), (b), and (c) above are corollaries to this result. This is Theorem 1.10 below.

We now present proofs of the three theorems mentioned above.

Theorem 1.8. *Let W be any word for which there are positive definite A and B such that $W(A, B)$ has an eigenvalue that is not positive. Then, for any positive integer k , there are positive definite letters such that W^k has a nonpositive eigenvalue.*

Proof. Let A, B be positive definite matrices that give W a nonpositive eigenvalue, and let λ be such an eigenvalue. If $k \in \{1, 2, 3, \dots\}$, then an eigenvalue of $W(A, B)^k$ is λ^k . If λ^k is nonpositive, we are done, so the problem lies in the possibility that $\lambda^k > 0$. It will be necessary, therefore, in this case to create a new pair of positive definite matrices A' and B' that give $W(A', B')^k$ a nonpositive eigenvalue.

We first offer a description of our approach before presenting the details that follow. The idea is to parameterize a pair of positive definite matrices in terms of a real variable t , $0 \leq t \leq 1$, and then examine the eigenvalues of the word W^k evaluated at those matrices. Using the continuity of eigenvalues on matrix entries, we then show that $W(A(t), B(t))^k$ cannot have positive eigenvalues for all $0 \leq t \leq 1$.

Let λ_A be the largest eigenvalue of A , and let λ_B be the largest eigenvalue of B . Define the following parameterization:

$$A(t) = t \cdot (\lambda_A I - A) + A \quad \text{and} \quad B(t) = t \cdot (\lambda_B I - B) + B \quad \text{for } 0 \leq t \leq 1.$$

We first note that $A(t)$ and $B(t)$ are positive definite for all such t since $(\lambda_A I - A)$ and $(\lambda_B I - B)$ are positive semidefinite by a simple eigenanalysis. Next, notice that $A(1) = \lambda_A I$ and $B(1) = \lambda_B I$, giving $W(A(1), B(1))$ positive eigenvalues. Additionally, $A(0) = A$ and $B(0) = B$, which shows that $W(A(0), B(0))$ has a nonpositive eigenvalue, by assumption. Since the eigenvalues of a matrix depend continuously on its entries [HJ, p. 539], the eigenvalues of $W(A(t), B(t))$ also depend continuously on t .

For $t \in [0, 1]$, the spectrum of $W(A(t), B(t))$ cannot contain 0 because each product, $W(A(t), B(t))$, has positive determinant. Now, let

$$\Gamma = \{t \in [0, 1] \mid W(A(t), B(t)) \text{ has a positive spectrum}\}.$$

Clearly, this set is not empty as $1 \in \Gamma$, and it is not the entire interval as $0 \notin \Gamma$. A straightforward continuity argument also shows that Γ is closed. Let t_M be the greatest lower bound of Γ , and notice that from above, $t_M \neq 0$ and $t_M \in \Gamma$. As a result, the eigenvalues of $W(A(t_M), B(t_M))$ are all positive. By continuity again, we can choose $t < t_M$ such that the eigenvalues of $W(A(t), B(t))$ are as close to the eigenvalues of $W(A(t_M), B(t_M))$ as we wish.

We are now ready to prove the theorem. Let k be a positive integer. By continuity, choose $t < t_M$ such that there is an eigenvalue, λ , of $W(A(t), B(t))$ with an argument θ satisfying $-\pi/k < \theta < \pi/k$ (see Figure ??). This guarantees that λ^k cannot be real. Our new pair $A(t), B(t)$ now proves the word W^k can have nonpositive eigenvalues. \square

Theorem 1.9. *If j and k are positive integers such that $j \neq k$, then there is a real, quasi-positive matrix T such that $T^k(T^*)^j$ has negative trace.*

Proof. We first note that we can assume $k > j$, since if $k < j$, we examine $[T^k(T^*)^j]^*$. We also assume without loss of generality that T has 1 for an eigenvalue and it is the smallest eigenvalue of T .

Using Schur triangularization, we suppose

$$T = \begin{bmatrix} 1 & x & z \\ 0 & a & y \\ 0 & 0 & b \end{bmatrix},$$

with $x, y, z \in \Re$ and $b > a > 1$.

Since it is necessary to compute powers of T , we note that

$$T^k = \begin{bmatrix} 1 & X_k & Z_k \\ 0 & a^k & Y_k \\ 0 & 0 & b^k \end{bmatrix} = \begin{bmatrix} 1 & X_{k-1} & Z_{k-1} \\ 0 & a^{k-1} & Y_{k-1} \\ 0 & 0 & b^{k-1} \end{bmatrix} \begin{bmatrix} 1 & x & z \\ 0 & a & y \\ 0 & 0 & b \end{bmatrix},$$

in which $X_k(Y_k; Z_k)$ is the 1,2 (2,3; 1,3) entry of T^k , $k > 0$.

The above expression allows us to find formulae for the entries of T^k by way of the following obvious recurrences:

$$X_k = x + aX_{k-1}; \quad Y_k = ya^{k-1} + bY_{k-1}; \quad Z_k = z + yX_{k-1} + bZ_{k-1}.$$

An easy induction gives us that

$$\begin{aligned} X_k &= x \frac{a^k - 1}{a - 1}; \quad Y_k = y \frac{a^k - b^k}{a - b}; \\ Z_k &= xy \frac{1}{a - 1} \cdot \left(\frac{a^k - b^k}{a - b} - b^{k-1} - \frac{b^{k-1} - 1}{b - 1} \right) + z \frac{b^k - 1}{b - 1} = xyC_k + zD_k, \end{aligned}$$

in which $C_k = \frac{1}{a - 1} \cdot \left(\frac{a^k - b^k}{a - b} - b^{k-1} - \frac{b^{k-1} - 1}{b - 1} \right)$, $D_k = \frac{b^k - 1}{b - 1}$ depend only on a , b , and k .

Thus, the trace of $T^k(T^*)^j$ can be computed explicitly in terms of x, y, z, a, b, k, j . It is

$$\begin{aligned} \text{Tr}[T^k(T^*)^j] &= \text{Tr} \left[\begin{pmatrix} 1 & X_k & Z_k \\ 0 & a^k & Y_k \\ 0 & 0 & b^k \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ X_j & a^j & 0 \\ Z_j & Y_j & b^j \end{pmatrix} \right] \\ &= (1 + X_k X_j + Z_k Z_j) + (a^{k+j} + Y_k Y_j) + b^{k+j} \\ &= 1 + a^{k+j} + b^{k+j} + x^2 \frac{a^k - 1}{a - 1} \cdot \frac{a^j - 1}{a - 1} + y^2 \frac{a^k - b^k}{a - b} \cdot \frac{a^j - b^j}{a - b} \\ &\quad + x^2 y^2 C_k C_j + x y z (C_k D_j + C_j D_k) + z^2 D_k D_j. \end{aligned}$$

Fix $a, b > 1$ and set $y = x$. Now, view $\text{Tr}[T^k(T^*)^j]$ as a quadratic polynomial in z . For this polynomial to take on negative values, it is necessary and sufficient for its discriminant to be positive. This discriminant is a quartic polynomial in x ; therefore, if we can show that its leading coefficient is always positive, this will demonstrate that for large enough values of x , the discriminant will also be positive. The coefficient of x^4 in this discriminant is

$$\begin{aligned} &(C_k D_j + C_j D_k)^2 - 4 D_k D_j (C_k C_j) \\ &= C_k^2 D_j^2 + 2 C_k C_j D_k D_j + C_j^2 D_k^2 - 4 C_k C_j D_k D_j = (C_k D_j - C_j D_k)^2. \end{aligned}$$

When $k = j$, the expression above is 0, so it is necessary to prove that whenever $k \neq j$, $C_k D_j \neq C_j D_k$. Examining $C_k D_j - C_j D_k$, this is equivalent to proving that

$$a^j b^{k+1} - a^k + b^k + a^k b - b^{k+1} + a^k b^j - a^k b^{j+1} - a^j b^k - b^j + a^j - a^j b + b^{j+1}$$

is never zero unless $k = j$. Factoring out $(b - 1)$, we need only prove that

$$f(a, b) = a^j b^k + a^k - b^k - a^k b^j + b^j - a^j$$

is never zero unless $k = j$. Examine the following polynomial in x :

$$g(x) = f(a, x) = x^k(a^j - 1) + x^j(1 - a^k) + a^k - a^j.$$

It is easy to see that $g(1) = 0$ and $g(a) = 0$. From Descartes's rule of signs, it is clear (since $a > 1$) that g has either 0 or 2 positive real roots. Since a and 1 are two such roots, g has no more positive ones. Hence, $g(b) \neq 0$ for $b \neq 1, a$.

This concludes the proof that $T^k(T^*)^j$ will have negative trace for some quasi-positive matrix T . Note that a description of all 3-by-3 quasi-positive T that give $T^k(T^*)^j$ a negative trace is implicit in the proof. \square

Our first corollary to this theorem is that the word $(BA)^2AB$ gives a negative answer to Question 2; but moreover, we also now have a description of all 3-by-3 positive definite A and B that give $(BA)^2AB$ a negative trace. Theorem 1.9 describes all 3-by-3 quasi-positive matrices T that give T^2T^* a negative trace, and hence all positive definite matrices A and B are given by $T = BA$ from Lemma 1.2.

We now prove the following.

Theorem 1.10. *For integers $p, q \geq 2$ and the word $W = ABA^pB^q$, there exist positive definite matrices A and B such that $W(A, B)$ has a negative trace.*

Proof. We first record a few preliminaries.

Let $F(p, q) = \text{Tr}[ABA^pB^q] = \text{Tr}[BAB^qA^p]$ be the desired trace of the word W . Now, suppose $A = U^*DU$ and $B = V^*EV$ are fixed positive definite matrices with U, V (real) orthogonal, and let $D = \text{diag}(a, b, c)$, $E = \text{diag}(r, s, t)$, $a, b, c, r, s, t > 0$. Then we can write

$$F(p, q) = \text{Tr}[UBAB^qU^*D^p] = \text{Tr}[VABA^pV^*E^q].$$

From these two expressions, it is clear that

$$(1) \quad F(p, q) = g_1(q)a^p + g_2(q)b^p + g_3(q)c^p,$$

$$(2) \quad F(p, q) = h_1(p)r^q + h_2(p)s^q + h_3(p)t^q,$$

where $g_i(q)$, $h_i(p)$ are linear functions in r^q, s^q, t^q and a^p, b^p, c^p , respectively. Equations (1) and (2) can be viewed as a generalization of the well-known expression for computing Fibonacci numbers. In fact, these equations imply the recurrence relations

$$(\mathfrak{F})(p, q) = (a + b + c)F(p - 1, q) - (ab + bc + ac)F(p - 2, q) + (abc)F(p - 3, q),$$

$$(\mathfrak{F})(p, q) = (r + s + t)F(p, q - 1) - (rs + rt + st)F(p, q - 2) + (rst)F(p, q - 3).$$

We are now ready to prove the result. It turns out that A_1 and B_1 (as described above) will prove the claim

$$A_1 = \begin{bmatrix} 1 & 20 & 210 \\ 20 & 402 & 4240 \\ 210 & 4240 & 44903 \end{bmatrix}, \quad B_1 = \begin{bmatrix} 36501 & -3820 & 190 \\ -3820 & 401 & -20 \\ 190 & -20 & 1 \end{bmatrix}.$$

The values of $(a + b + c)$, $(ab + bc + ac)$, (abc) , $(r + s + t)$, $(rs + st + rt)$, and (rst) are obtained from the characteristic polynomials of A and B . These polynomials are easy to compute as $P_A(t) = t^3 - 45306t^2 + 74211t - 6$ and $P_B(t) = t^3 - 36903t^2 + 44903t - 1$. Therefore, (3) and (4) become

$$(5) \quad F(p, q) = 45306 \cdot F(p - 1, q) - 74211 \cdot F(p - 2, q) + 6 \cdot F(p - 3, q),$$

$$(6) \quad F(p, q) = 36903 \cdot F(p, q - 1) - 44903 \cdot F(p, q - 2) + F(p, q - 3).$$

To prove the theorem, we must show that $F(p, q) < 0$ for all $p, q \geq 2$. First notice that for the base cases of $2 \leq p, q \leq 4$, we have that $F(p, q)$ are given by the following table:

	$q = 2$	$q = 3$	$q = 4$
$p = 2$	-3164	-171233664	-6318893781764
$p = 3$	-219049002	-10537988104302	-388873536893369802
$p = 4$	-9923997300324	-477421308542380824	-17617832833924812095724

To prove the result using the recurrences above, we will invoke induction and prove something stronger. Namely, we claim that for all $p, q \geq 2$, $F(p, q) < 0$ and also the following inequalities hold:

$$F(p, q) < 10 \cdot F(p - 1, q) \quad \text{for } p > 2,$$

$$F(p, q) < 10 \cdot F(p, q - 1) \quad \text{for } q > 2.$$

Suppose the result is true for all $2 \leq p, q < N$ (from the table above, we can also suppose $N \geq 5$); then we want to show it true for $2 \leq p, q \leq N$. For $2 \leq p, q < N$, examine $F(N, q)$, $F(p, N)$, and $F(N, N)$. From (5) and (6), we have

$$\begin{aligned}
 (7) \quad F(N, q) &= 45306 \cdot F(N-1, q) - 74211 \cdot F(N-2, q) + 6 \cdot F(N-3, q) \\
 &< 45306 \cdot F(N-1, q) - 7421.1 \cdot F(N-1, q) \\
 &= 37884.9 \cdot F(N-1, q) < 10 \cdot F(N-1, q), \\
 F(p, N) &= 36903 \cdot F(p, N-1) - 44903 \cdot F(p, N-2) + F(p, N-3) \\
 (8) \quad &< 36903 \cdot F(p, N-1) - 4490.3 \cdot F(p, N-1) \\
 &= 32412.7 \cdot F(p, N-1) < 10 \cdot F(p, N-1).
 \end{aligned}$$

But to complete the induction, we must also show that $F(N, N) < 10 \cdot F(N-1, N)$ and $F(N, N) < 10 \cdot F(N, N-1)$. Substituting (6) into the right-hand side of (5) with $p = N$, $q = N$, we have

$$\begin{aligned}
 (9) \quad F(N, N) &= 1671927318 \cdot F(N-1, N-1) - 2034375318 \cdot F(N-1, N-2) \\
 &\quad + 45306 \cdot F(N-1, N-3) \\
 &\quad - 2738608533 \cdot F(N-2, N-1) + 3332296533 \cdot F(N-2, N-2) \\
 &\quad - 74211 \cdot F(N-2, N-3) \\
 &\quad + 221418 \cdot F(N-3, N-1) - 269418 \cdot F(N-3, N-2) \\
 &\quad + 6 \cdot F(N-3, N-3) \\
 &< 1671927318 \cdot F(N-1, N-1) - 203437531.8 \cdot F(N-1, N-1) \\
 &\quad - 273860853.3 \cdot F(N-1, N-1) - 74.211 \cdot F(N-1, N-1) \\
 &\quad - 269.418 \cdot F(N-1, N-1) \\
 &= 1194628589.271 \cdot F(N-1, N-1).
 \end{aligned}$$

But from (8) with $p = N-1$, we have

$$\begin{aligned}
 36903 \cdot F(N-1, N-1) &= F(N-1, N) + 44903 \cdot F(N-1, N-2) - F(N-1, N-3) \\
 &< F(N-1, N) - (1/100) \cdot F(N-1, N-1).
 \end{aligned}$$

Therefore, $36903.01 \cdot F(N-1, N-1) < F(N-1, N)$, which gives us easily (from (9)) that

$$F(N, N) < 1194628589.271 \cdot F(N-1, N-1) < 10 \cdot F(N-1, N).$$

To arrive at $F(N, N) < 10 \cdot F(N, N-1)$, we perform the same examination, this time with (7):

$$F(N, N-1) = 45306 \cdot F(N-1, N-1) - 74211 \cdot F(N-2, N-1) + 6 \cdot F(N-3, N-1),$$

giving us the inequality $45306.06 \cdot F(N-1, N-1) < F(N, N-1)$.

So again, from (9), we see that $F(N, N) < 10 \cdot F(N, N-1)$. This completes the induction and shows that for all $p, q \geq 2$, $F(p, q) < 0$. The proof also bounds the growth from below, but the factor of 10 is obviously not the best possible. \square

At this point, we should remark that the proof for Theorem 1.10 above could be generalized to a certain extent. Namely, suppose W is a word that can be written as $W_1 A^p W_2 B^q$ for some words W_1, W_2 in A and B . Then, A_1 and B_1 give this word

negative trace for all integers $p, q \geq 2$ provided that for the base cases of $2 \leq p, q \leq 4$,

$$F(p, q) < 0; \quad F(p, q) < 10 \cdot F(p-1, q); \quad \text{and} \quad F(p, q) < 10 \cdot F(p, q-1).$$

As an example, a calculation gives us that for the word $W = ABABA^p B^q$ the first 9 values of $F(p, q)$ are given by¹

	$q = 2$	$q = 3$	$q = 4$
$p = 2$	-32302	-1319655482	-48697748014592
$p = 3$	-1748875224	-70292975950848	-2.59394099689082e+018
$p = 4$	-79232137801728	-3.18459541653658e+018	-1.17517468821039e+023

The word $W = ABBABA^p B^q$ also satisfies the base case conditions as the $F(p, q)$ are

	$q = 2$	$q = 3$	$q = 4$
$p = 2$	-222790424	-10720038844524	-3.95591587257758e+017
$p = 3$	-10103386100406	-4.86025787321779e+017	-1.79353558546523e+022
$p = 4$	-4.57727477164142e+017	-2.20190887755731e+022	-8.12549875102683e+026

It should now be clear that we conjecture the following.

Conjecture 1.11. A word has positive trace for every pair of positive definite letters if and only if the word is nearly symmetric.

Using the results and ideas we have discussed, it is possible to verify this conjecture for words of lengths less than 11. Before listing these results, we remark on how to find specific A and B for which a word has negative trace. One difficulty is how to view the set of positive definite matrices A and B . We explain a helpful parametric approach for the sample word $BAABBAAA$ and the generalization will be clear. Notice that we do not yet know that this word can have a negative trace using any of the methods thus far.

First set $Q = AB$, and recall that all solutions A, B to such an equation are given by Lemma 1.2 as $Q = SDS^{-1}$, $A = SES^*$, $B = S^{-1*}E^{-1}DS^{-1}$, in which D is a positive diagonal matrix, and E is a positive definite matrix commuting with D . For simplicity, we seek a positive diagonal E . Using these substitutions and some simplification, our original word has the same eigenvalues as the following expression: $DPDP^{-1}DPEPE$, in which $P = S^*S$.

Next, fix a positive definite matrix P and view the positive diagonal matrices D and E parametrically, hoping now to minimize the trace of the product above. These minimizations are easier to perform because now we have a simple parametric description of positive definite pairs. Notice that it is not necessary to find A and B to show that they exist and give the word a negative trace. However, it is useful to have explicit examples, as they may be later used to show that other (not nearly symmetric) words admit negative trace. After finding D, E , and P , we recover

¹While values are integers, they are shown only to the first 15 significant digits.

TABLE 1. All words that are not nearly symmetric of length < 11 admit negative trace.

$AABABB$	Original solution A_1, B_1 using C^2C^T
$AAABABB$	Theorem 1.10
$AAAABABB$	Theorem 1.10
$AAABAABB$	Using A_2, B_2
$AAABABBB$	Theorem 1.10
$AABABABB$	Equivalent to $(AB)^3BA$
$AAAAABABB$	Theorem 1.10
$AAAABAABB$	Equivalent to $(A^2B)^2BA^2$
$AAAABABBB$	Theorem 1.10
$AAABAABAB$	Using A_3, B_3 produced by the technique above
$AAABAABBB$	Using A_2, B_2
$AAABABABB$	Theorem 1.10
$AABAABABB$	Theorem 1.10
$AAAAAABABB$	Theorem 1.10
$AAAAABAABB$	Using A_2, B_2
$AAAAABABBB$	Theorem 1.10
$AAAABAABBB$	Using A_4, B_4 produced by the technique above
$AAAABAABAB$	Using A_3, B_3
$AAAABAABBB$	Using A_2, B_2
$AAAABABABB$	Theorem 1.10
$AAAABABBBB$	Theorem 1.10
$AAAABBABBB$	Using A_2, B_2 (interchanging A and B)
$AAABAABABB$	Theorem 1.10
$AAABAABBBAB$	Using A_1, B_1
$AAABABAABB$	Using A_2, B_2
$AAABABABBB$	Using A_2, B_2
$AAABABBABB$	Theorem 1.10
$AAABBAABBB$	Using A_5, B_5 produced by the technique above
$AABABABABB$	Equivalent to $(AB)^4BA$
$AABABABBAB$	Equivalent to $(AB)^3(BA)^2$
$AABABBAABB$	(d)

these letters from the equations $S^*S = P$, $A = SES^*$, $B = S^{-1*}E^{-1}DS^{-1}$. An example solution found using this technique for the word $BAABBAAA$ is given by

$$A_2 = \begin{bmatrix} 4351/479 & 4856/399 & 18421/62 \\ 4856/399 & 16073/64 & 3784/21 \\ 18421/62 & 3784/21 & 89917/9 \end{bmatrix},$$

$$B_2 = \begin{bmatrix} 2461/149 & -297/641 & -757/1569 \\ -297/641 & 179/6146 & 50/3767 \\ -757/1569 & 50/3767 & 269/19081 \end{bmatrix}.$$

It is easily verified that the trace of the word $BAABBAAA$ is a negative rational number given approximately by $\text{Tr}(BAABBAAA) \approx -143370.8471$.

In Table 1 we list all the equivalence classes of words that are not nearly symmetric and are of length less than 11. Next to each word, we describe the method of finding the A and B that proves they can have a negative trace.

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REFERENCES

- [BMV] D. BESSIS, P. MOUSSA, AND M. VILLANI, *Monotonic converging variational approximations to the functional integrals in quantum statistical mechanics*, J. Math. Phys., 16 (1975), pp. 2318–2325.
- [HJ] R. HORN AND C. R. JOHNSON, *Matrix Analysis*, Cambridge University Press, New York, 1985.
- [K] R. KEMP, *On the number of words in the language $\{w \in \Sigma^* \mid w = w^R\}^2$* , Discrete Math., 40 (1982), pp. 225–234.
- [L] E. LIEB, *private communication*.
- [P] S. PIERCE, *private communication*.
- [S] I. SPITKOVSKY, *private communication*, Williamsburg, VA, 1999.

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